

THE RAPID X-RAY VARIABILITY OF V4641 SAGITTARII (SAX J1819.3-2525 = XTE J1819-254)

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ABSTRACT

We report on the rapid X-ray variability of the variable star and X-ray transient V4641 Sagittarii (SAX J1819.3–2525; XTE J1819–254) as observed on 15 Sept. 1999 by the proportional counter array (PCA) on board the *Rossi X-ray Timing Explorer* (*RXTE*). During the first ~ 900 s of the first PCA observation, V4641 Sgr showed very strong X-ray fluctuations by a factor of 4 on time scales of seconds to about 500 on time scales of minutes. The spectrum of the source during this flaring episode became harder when the count rate decreased. After this flaring episode, V4641 Sgr entered a quiescent state in which it remained for the rest of this, and the subsequent PCA observations. The X-ray spectrum was considerably softer in this quiescent state than during the flaring episode. The intrinsic X-ray luminosity (both during the flaring episode and the quiescent state) and the rapid X-ray variability do not strongly constrain the nature of the compact object (neutron star or black hole) in the system, although a black hole seems to be more likely. The very short duration of the bright X-ray phase of V4641 Sgr and its likely close distance suggest that many similar objects could be present in our galaxy, most of which are not noticed when they are in X-ray outburst due to the short duration of these outbursts. A considerable number of the black holes present in our galaxy might be contained in systems similar to V4641 Sgr.

Subject headings: accretion, accretion disks — stars: individual (V4641 Sgr, SAX J1819.3–2525, XTE J1819–254) — X-rays: stars

1. INTRODUCTION

In Feb. 1999, a new X-ray transient was independently discovered by *BeppoSAX* (SAX J1819.3–2525; in ‘t Zand et al. 1999) and *RXTE* (XTE J1819–254; Markwardt, Swank, & Marshall 1999a). Its position is consistent with that of the variable star V4641 Sgr (note that V4641 Sgr had been misidentified as GM Sgr [see IAU Circular 7277]). Its 2–10 keV flux varied between <1 and 80 mCrab (in ‘t Zand et al. 1999; Markwardt et al. 1999a). On 15 Sept. 1999, the source rapidly increased in the optical (Stubbings 1999) and with the *RXTE* All-Sky Monitor (ASM) its 2–12 keV intensity was observed to increase very

rapidly (within 7 hours) from 1.6 to 12.2 Crab (Smith, Levine, & Morgan 1999a,b). Subsequent ASM measurements showed that within two hours of this flare, the flux had declined down to a level only marginally detectable with the ASM (<50 mCrab; Smith et al. 1999c).

Optical and infrared spectra taken during this bright X-ray event show emission lines (Ayani & Peiris 1999; Liller 1999; Djorgovski et al. 1999; Charles, Shahbaz, & Geballe 1999), reminiscent of accretion of matter onto a compact object, demonstrating that V4641 Sgr is indeed the optical counter part. On 16 Sept. 1999, VLA observations were taken and a radio source was discov-

ered (Hjellming, Rupen, & Mioduszewski 1999a) at a position consistent with V4641 Sgr. Follow up VLA and ATCA observations showed that its flux was rapidly declining on time scales of hours to days (Gaensler et al. 1999; Hjellming, Rupen, & Mioduszewski 1999b; Hjellming et al. 1999c). The VLA observations also showed that it was resolved, demonstrating the presence of ejecta (Hjellming et al. 1999b,c).

On 15 Sept. 1999, a short (3000 s) pointing was taken with the *RXTE* proportional counter array (PCA). A rapidly variable source was observed with a flaring and a quiescent episode (Markwardt, Swank, & Morgan 1999b). No pulsations or quasi-periodic oscillations (QPOs) were detected but red noise below 30 Hz was present. Here, we discuss in more detail the rapid X-ray variability as observed with the PCA during this observation.

2. OBSERVATION AND RESULTS

Several public TOO PCA observations were scheduled between 15 and 18 Sept. 1999 for a total of ~ 33 ksec on-source time. However, only the first 1500 s of the first observation (on 15 Sept. 1999 21:18–22:43 UTC; see also Markwardt et al. 1999b) showed very high fluxes and strong variability. We limited our analysis to these first 1500 s in order to study the X-ray variability of the source. During the second 1500 s of this observation and during the later observations, V4641 Sgr could still be detected with the PCA, but at a very low flux level (< 100 counts s^{-1} for 5 detectors on; 2–60 keV) and no significant variability could be detected (upper limits of 5%–40% rms [2–22.1 keV; 0.01–100 Hz; depending on total on-source time and source count rate during the individual observations] on band limited noise similar to that detected during the first ~ 900 s of the first observation [see below]).

During the PCA observations, data were accumulated in several different modes which were simultaneously active. Here, we used data obtained with the 'Binned' modes B_250US_1M_0.249_H (one photon energy channel [effective range of 2–60 keV] and 244 μs time resolution) and B_4M.8B.0.49_H (eight channels covering 2–22.1 keV and 3.9 ms time resolution). These data were used to calculate 128 s FFTs to create the power spectra and the cross spectra, the 3.9 ms data were used to create light curves, a hardness-intensity diagram, and a hardness curve. The

power spectra were fitted with a function consisting of a constant (the dead-time modified Poisson level) and a broken power law (the band-limited noise below ~ 100 Hz). A Lorentzian was used to determine upper limits (95% confidence level) on the rms amplitude of QPOs above 100 Hz, assuming a QPO width of 50 Hz. To correct for the small dead-time effects on the lags, we subtracted the average 50–125 Hz cross-vector from the cross spectra (van der Klis et al. 1987).

The 2–22.1 keV light curve of the first 1500 s of the first PCA observation is shown in Figure 1a, showing the flaring behavior of V4641 Sgr between 300 and 900 s from the start. After 1000 s, the source enters a quiescent state, with one last flare between 1010 and 1060 s (Fig. 1c). After that (and also in the second 1500 s of this observations, and in the other observations) it remained in this state at very low count rates (see also Markwardt et al. 1999b). During the flaring episode, it varied rapidly in count rate. On time scales of 5–10 minutes it varied in luminosity by a factor of up to 500. Within one second, it sometimes increased and then decreased by more than a factor of 4 (Figs. 1b and d).

The strong variability is also evident from the power spectra obtained from the first 896 s (see Fig. 2a). Strong band-limited noise ($47.2\% \pm 0.8\%$ rms amplitude; 0.01–100 Hz; 2–22.1 keV) can clearly be seen. Its shape fits a broken power law with the break at 5.1 ± 0.2 Hz and an index below and above the break of 1.03 ± 0.02 and 2.16 ± 0.03 , respectively. The rms amplitude decreases from $\sim 54\%$ to $\sim 35\%$ as a function of energy, increasing from ~ 4 keV to ~ 20 keV (Fig. 3a). By subtracting the 3.9 ms data (2–22.1 keV) from the 244 μs data (2–60 keV), we could make a power spectrum for the data above 22.1 keV. The rms amplitude of the noise was even less, $30.6\% \pm 0.5\%$, above 22.1 keV (effective range of 22.1–60 keV). To show the decrease of amplitude below 20 keV more clearly, we excluded this point from the figure. The noise also has significant hard phase lags between photons with energies of 2–9.7 keV and those with energies of 9.7–22.1 keV (Fig. 2b). The lags increased from being consistent with zero below 0.1 Hz to ~ 0.1 rad at ~ 0.03 Hz. Above this frequency, the lags decreased again and above about 10 Hz the lags were consistent with zero again. We studied the energy dependence of the lags for four frequencies intervals: 0.02–0.1 Hz (Fig. 3b), 0.1–1.0 Hz (Fig. 3b), 1.0–10.0 Hz

(Fig. 3*b*), and 10.0–50.0 Hz (not shown, the lags were always consistent with zero). Although the lags in the range 0.02–0.1 Hz were barely significant (Fig. 3*b*) a clear trend with energy was present.

In the power spectrum obtained from the 244 μ s data, no QPOs above 100 Hz were detected (upper limits of 2% rms). However, these data cover the whole *RXTE* energy band. Therefore, such QPOs could have been present but undetectable if their strength depended strongly on energy, similar to the kHz QPOs observed in many neutron star and some black hole systems (van der Klis 1998, 1999; Remillard et al. 1999; Homan, Wijnands, & van der Klis 1999). From the 3.9 ms data, we made a hardness-intensity diagram (Fig. 4*a*) and a hardness curve (*b*) with a time resolution of 2 s. For comparison, we also plotted the 2–22.1 keV light curve (Fig. 4*c*). As hardness we used the count rate ratio between 9.7–22.1 keV and 2–9.7 keV and as intensity the 2–22.1 keV count rate, but plotted on a logarithmic scale to show the variations more clearly. From Figure 4*a*, it is clear that during the flaring episode the hardness decreased when the count rate increased. When the transition to the quiescent state occurred the source became softer. During the last flare (in the quiescent state; Fig. 1*c*), the overall hardness was less than for the flares during the flaring episode.

3. DISCUSSION

We have presented the X-ray variability of V4641 Sgr during its 1999 Sept. 15 bright event. It shows strong variations by a factor of 4 on time scales of seconds to variations by a factor of ~ 500 on time scales of minutes. These strong variations are also evident in the power spectrum by the presence of strong (30%–55% rms amplitude, depending on energy) band-limited noise. Assuming the most likely distance of 0.5–1.0 kpc (Hjellming et al. 1999c; obtained by performing an HI absorption experiment against the radio counter part) and using the maximum flux during our PCA observation (Markwardt et al. 1999b), the maximum intrinsic luminosity (2–60 keV) was $0.3\text{--}1.0 \times 10^{37}$ erg s $^{-1}$ (note that it was at considerable higher luminosities during the ASM measurements). This luminosity, the strong variability on short time scales, and the presence of optical and infrared emission lines (see § ??) suggest that the X-rays are produced by accretion onto a

compact object.

The exact nature of the compact object is difficult to determine. The likely intrinsic luminosity and the hardness of the spectrum (Markwardt et al. 1999b; see Smith et al. 1999c for a more detailed analysis) strongly indicate that accretion onto a white dwarf, a nova explosion, and thermonuclear burning on a white-dwarf surface cannot account for the X-ray emission and its properties. Compared to the intrinsically brightest low magnetic field neutron star and black hole systems, the luminosity of V4641 Sgr during our PCA observations was relatively low (the brightest systems have an luminosities of $> 10^{38\text{--}39}$ erg s $^{-1}$), which suggests that also the accretion rate was relatively low. At such low accretion rates, the rapid variability (van der Klis 1995; Wijnands & van der Klis 1999), including the phase lags (Ford et al. 1999), and the spectrum (e.g., Barret & Vedrenne 1994) of the low magnetic field neutron star and the black hole systems are very similar (van der Klis 1994), making it difficult to determine the exact nature of the compact object in V4641 Sgr. Although the very strong variability suggests a black hole primary in this system (usually such strong variability is only observed for the black-hole systems), it cannot be excluded that some neutron star systems can also exhibit such strong variability. The decrease of the strength of the variability in V4641 Sgr with energy is similar to what has been observed in several black-hole systems in their low state (e.g., Nowak et al. 1999a; Nowak, Wilms, & Dove 1999b), but the neutron star systems have not been studied in enough detail in this respect to allow detailed comparisons between the different types of systems.

It was suggested that the nature of the compact objects in X-ray transients could be determined by studying and comparing the X-ray emission properties of those systems in their quiescent state (see, e.g., Rutledge et al. 1999). The luminosity for V4641 Sgr in its quiescent episode during the first PCA observation was $0.5\text{--}2.2 \times 10^{34}$ erg s $^{-1}$ but monitoring observations with the PCA of the galactic-center region showed that during the last 7 months the luminosity had dropped occasionally to $0.6\text{--}2.4 \times 10^{33}$ erg s $^{-1}$ (see Markwardt et al. 1999b for the fluxes used). However, these luminosities do not give more insight in the nature of the compact object. Both the observed or derived upper limits on the luminosi-

ties for neutron star and black hole X-ray transients in quiescence are consistent with the values detected for V4641 Sgr in its quiescent episode. More detailed studies in quiescence are needed to determine the lowest observed luminosity in quiescence. If V4641 Sgr contains a black hole then it is expected that the luminosity should drop sometimes significantly below 10^{32} erg s $^{-1}$, as observed in other black-hole transients in quiescence.

Thus, the properties of V4641 Sgr as observed with the PCA are very similar to those observed for an accreting compact object which accretes matter from its companion star at a low rate. Although a neutron star primary cannot be excluded, the strong variability and the low intrinsic luminosity make an interpretation of V4641 Sgr as a black-hole candidate in the low state most favorable. The most promising way to determine the exact nature is to dynamically (during the quiescent state; from the optical line spectrum of the companion star) constrain the mass of the primary. If the primary is truly a black hole, then several features have been observed for V4641 Sgr which are not commonly observed in black hole systems in their low state. For example, its very strong variability have only been observed in a few other systems (e.g., GRS 1915+105: Greiner, Morgan, & Remillard 1996; Belloni et al. 1997; Taam, Chen, & Swank 1997; GS 2023+338: Terada et al. 1994; Oosterbroek et al. 1997). But a major difference is that the intrinsic luminosities of those sources were much higher (about $> 10^{39}$ erg s $^{-1}$; see, e.g., Belloni et al. 1997; Terada et al. 1994) than for V4641 Sgr. Another unusual property of V4641 Sgr is the very short time span of its bright X-ray event (< 10 hours). In this respect, V4641 Sgr is similar to the recently discovered transient CI Cam (Smith et al. 1998). However, several differences are also present. The outburst of CI Cam was on slightly longer time scales (days) and much more smooth (Belloni et al. 1999) than the event observed for V4641 Sgr, which exhibited very strong variability. So, although V4641 Sgr resembles several sources in some of its behavior, it differs from each of them significantly in other respects.

Reanalysis of the ASM archive revealed several similar short lived events for V4641 Sgr as the Sept. 15 event (Smith et al. 1999c), which went previously unnoticed. The Sept. 15 event was directly noticed because (a) more attention to V4641 Sgr was paid because of its sudden increase

in the optical (Stubbings 1999) and (b) this event was brighter (2–30 times) than the others. The short life times of the events and the strong flux fluctuations indicate that the accretion is very unstable and highly irregular and not much accretion takes place. The fact that several events went unnoticed suggest that many sources with similar events also fail to get noticed, especially when they are at a greater distance than V4641 Sgr and have therefore lower fluxes. The exact number of such sources in our galaxy is difficult to estimate because of the uncertainties in the distances and the recurrence time scales of their outbursts. However, if V4641 Sgr harbors a black hole, it is clear that a sizeable number of the black holes in our galaxy could be present in V4641 Sgr like systems.

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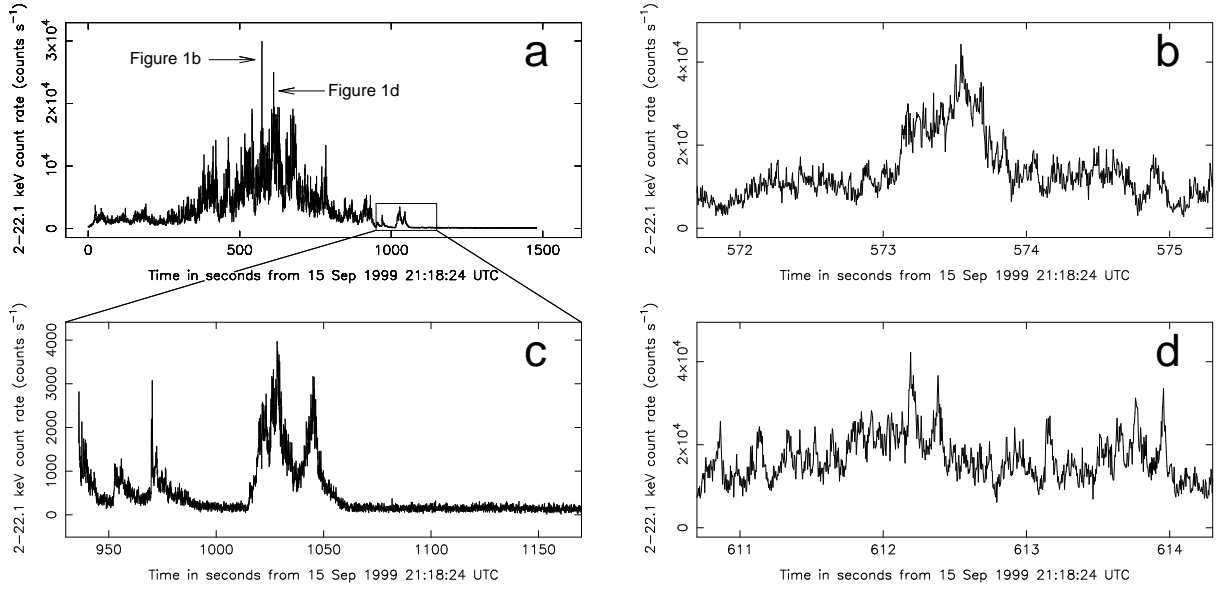


FIG. 1.— The 2–22.1 keV light curve of V4641 Sgr obtained from the 3.9 ms Binned mode data (*a*). Blow ups of the two brightest flares are shown in *b* and *d* and a blow up of the last flare and the quiescent emission is show in *c*. The time resolution is 0.25 seconds in *a*, 1/256 seconds (3.9 ms) in *b* and *d*, and 0.0625 seconds in *c*. The count rates are for 5 detectors but are not corrected for background or dead-time. The background varied between 50 and 65 counts s⁻¹ (2–22.1 keV) during the observation. The dead-time correction varied between 1% and 10%.

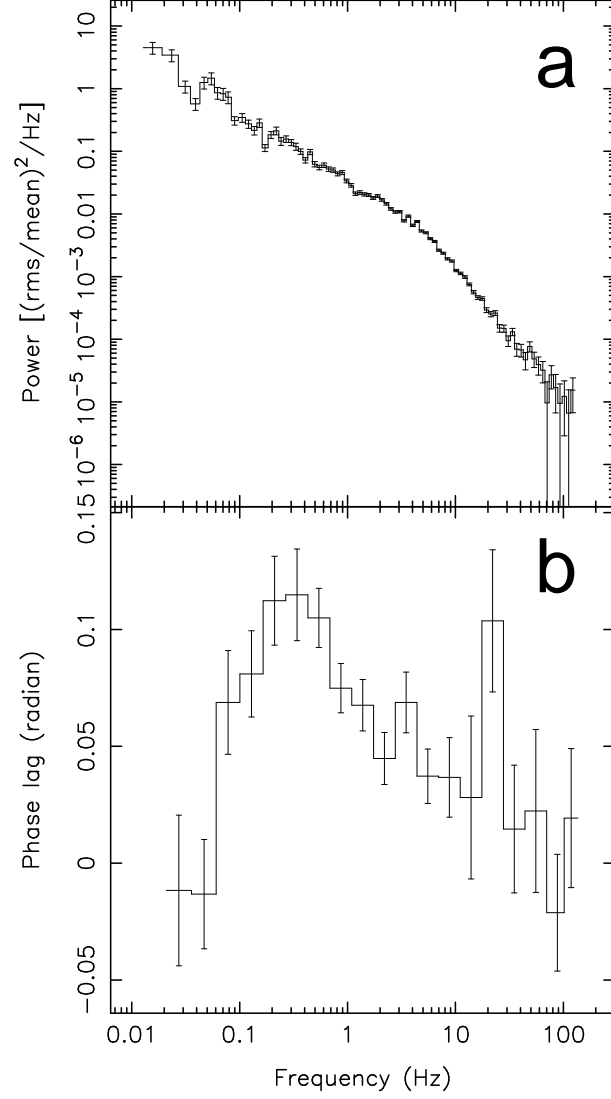


FIG. 2.— The power spectrum (a) and the cross spectrum (b) of the first 896 seconds of the first observation of V4641 Sgr (obtained from the 3.9 ms Binned mode data). The power spectrum was calculated for the energy range 2–22.1 keV. The cross spectrum was calculated between the energy bands 2–9.7 keV and 9.7–22.1 keV. Positive phase lags mean that the hard photons lag the soft ones.

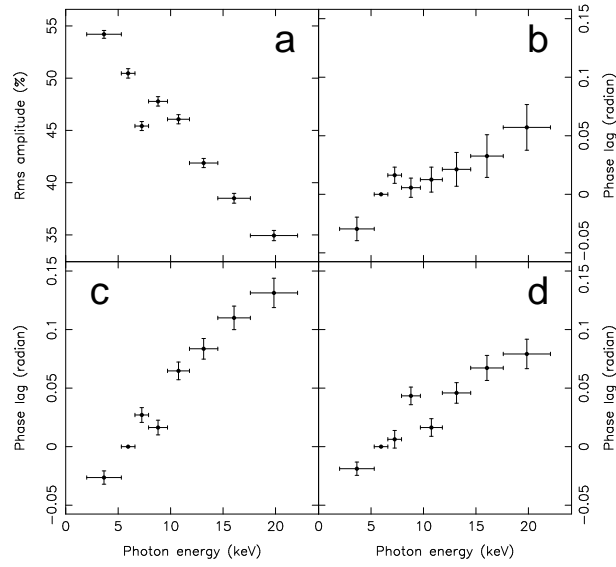


FIG. 3.— The rms amplitude (*a*) and the phase lags between 0.02–0.1 Hz (*b*), 0.1–1.0 Hz (*c*), and 1.0–10.0 Hz (*d*) of the broken power law as a function of photon energy. As a reference band in *b*–*d*, we used the energy band 5.3–6.6 keV. Positive phase lags mean that the hard photons lag the soft ones.

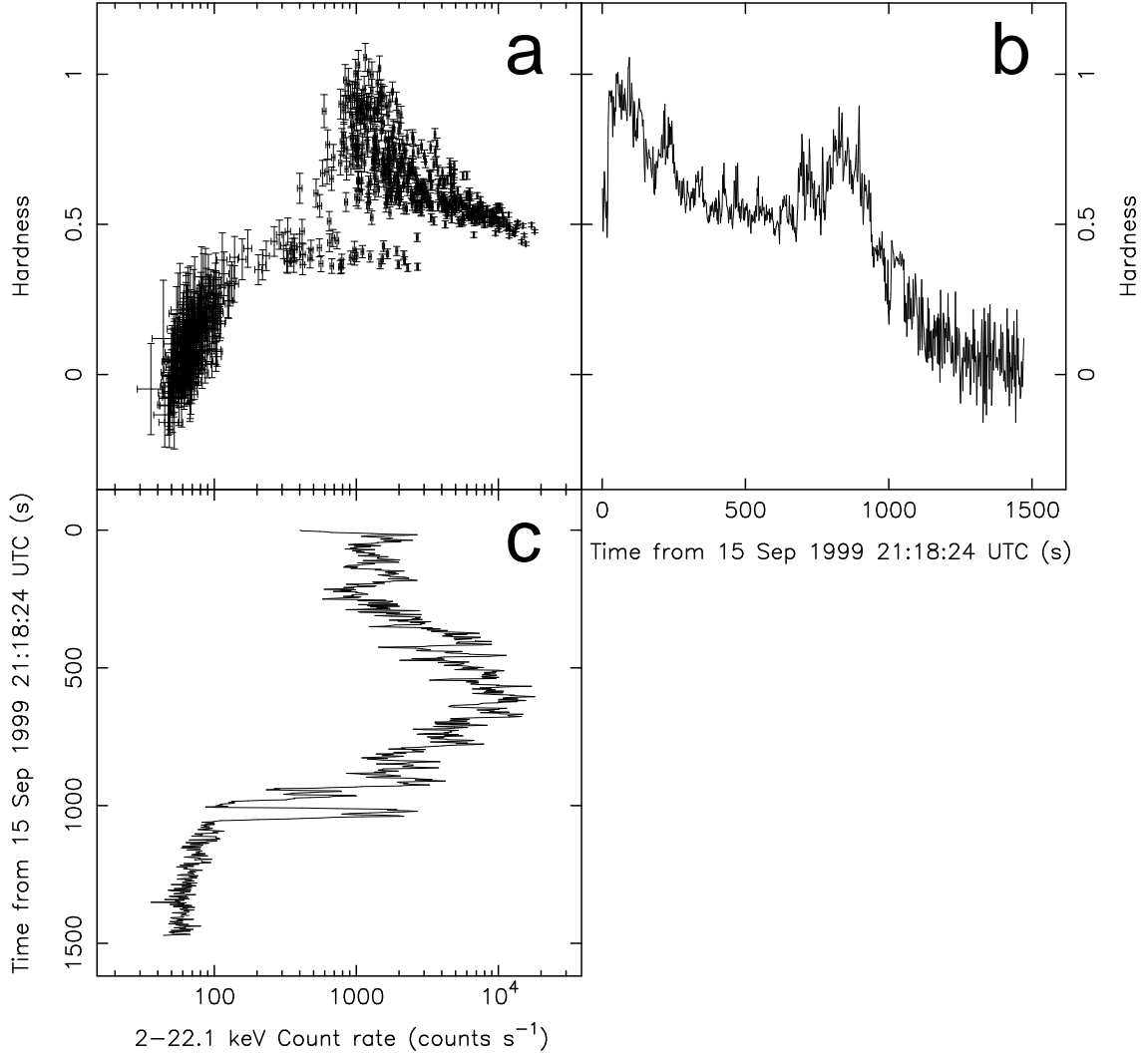


FIG. 4.— Hardness-intensity diagram (*a*), the hardness curve (*b*), and the light curve (*c*) as obtained with the 3.9 ms Binned mode data. The hardness is the count rate ratio between 9.7–22.1 keV and 2–9.7 keV. The intensity is the count rate for the energy range 2–22.1 keV. The time resolution is 2 seconds. The count rates are background subtracted but not dead-time corrected. The dead-time correction is between 1% and 10%.